System Islanding Using Minimal Cutsets with Minimum Net Flow

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Abstract-- **Slow coherency has effectively proved its capability in determining sets of generator groups among weak connections in any given power system. In this paper, we provide two comprehensive approaches to deal with islanding the actual system based on the grouping information, by using the minimal cutsets technique in graph theory. The issue of minimal cutsets has been widely discussed in areas related to network topology determination, reliability analysis, etc. The results of this paper also show potential in application to power system islanding. The verification of the islanding scheme is provided based on a WECC 179-Bus, 29-Generator test system.**

Index Terms- **Slow coherency based grouping, Graph theory, connected graph, path, minimal cutsets.**

I. Nomenclature

MINIMAL CUTSET: For a given graph G= (V, E), a subset of edges C⊂E is a minimal cutset if and only if deleting all edges in C would divide G into two connected components.

VERTICES CONTRACTION: Given a graph G and one adjacent vertices pair {x, y}∈V, we define G/{x, y}, the contraction of pair {x, y}, by deleting x and replacing each edge of the form {w, x} by an edge {w, y}. If this process creates parallel edges, we pick up one edge. We also delete any self-loops.

II. Introduction

WITH the advent of deregulation and restructuring, power systems are under increasing stress as deregulation introduces several new economic objectives for operation. Since the systems are being closely operated at their limits, weak connections, unexpected events, hidden failures in protection system, human errors, and a host of other reasons may cause the system to lose stability and even lead to catastrophic failure. For economic reasons, larger amounts of power are increasingly being transmitted over transmission lines. Following large disturbances, groups of generators tend to swing together. Attention has thus been drawn to the stability of interarea oscillations between groups of machines. These oscillations are lower in frequency than the local oscillations between machines that are electrically close. As a result, there is a separation in time scale between these two phenomena. Besides, several comprehensive software packages for computing these low frequencies in large power systems are available to analyze the participation of the machines in these oscillations.

In References [1],[2],[3],[4], and [5], the slow coherency approach based on the two-time-scale model has been successfully applied to the partitioning of the power system network into groups of coherent generators.

In the literature, there are some other approaches for the detection of islanding. In Reference [6], a spectral method for identifying groups of strongly connected sub-networks in a large-scale interconnected power system grid is presented as an alternative to the long-standing singular perturbation-based coherency techniques. Reference [7] introduces an algorithm based on the breadth first search (BFS) algorithm from graph theory for island detection and isolation. In Reference [8], an interesting method based on the occurrence of singularity in the Newton power flow is illustrated. Based on the voltage magnitude variation method of a distributed generation unit, Reference [9] gives an active technique for detecting the islanding. In [10], the authors present a method for system splitting by using OBDD technique. In the case of splitting system into two islands, each load bus either belongs to one island, or the other. This relationship can be captured by a Boolean variable. A software package called 'BuDDY' [11] has been conducted to decide the value of these Boolean variables in order to cap the generation and load imbalance within the limit in the island. However, for better system islanding, the dynamic characteristics of the system, namely dynamics of generators and loads, should be considered. Methods taking into consideration only steady state properties of the system are not efficient and as a result are time consuming. Slow coherency approach of generator grouping, which is widely studied in the literature, provides the potential of capturing the movement of generators between groups under disturbance. Therefore, in this approach, we use the slow coherency as our grouping technique.

Based on slow coherency, the generators in the system have been divided into several groups. For two interconnected generator groups, reference [12], [13] present an islanding method by constructing a small sub-network using the center bus, which is one of the buses in the group boundary. This sub-network is referred to as the interface network. A brute force search is then conducted on the interface network to determine the cutsets where the islands are formed. For each island candidate, the total load and generation are calculated, and the island with minimum load-generation imbalance is picked up as the optimal cutset if no other criteria have been considered. However, this approach involves more computational effort. Furthermore, it is system-specific. For

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some systems, it returns fairly good results, but not for others. In this research proposal, a new slow coherency grouping based approach by using minimal cutsets is presented to solve this type of problem.

Minimal cutsets has been previously investigated in communication, network topology, and network (particularly, power system) reliability analysis (maximum flow and connectivity) [14], [15], [16]. As shown in this paper, it also has the potential in determining where to actually island the system.

The paper is organized as follows. Section III provides an overview of the slow coherency theory and its application to determine the weakest link in the system and identify the appropriate grouping of generators. Section IV, begins with the brief introduction of other islanding approaches, describes the motivation of the new automatic islanding approach to form the islands. Furthermore, Section V presents two comprehensive approaches to system islanding. The approach is examined on a 29 Gen-179 Bus system in Section VI to verify the effectiveness of the grouping and islanding procedure. The conclusions and consideration of future work are provided in section VII.

III. Slow Coherency based Grouping

A. Brief Introduction

In the controlled islanding self-healing approach, it is critical to determine the islands for a given operating condition. An elegant and flexible approach to islanding can result in significant benefit to the post fault corrective control actions that follow the islanding. These include the load shedding procedure and to the load restoration procedure. Generally, islanding is system dependent. [12] indicates that the choice of these islands is almost disturbance independent, which makes it easy to implement a fairly general corrective control scheme for a given system.

Slow coherency has originally been used in the development of dynamic equivalents for transient stability studies. Several methods have been used to identify the coherent groups of generators [2], [18]. In these methods, two assumptions are made:

1) The coherent groups of generators are almost independent of the size of the disturbance.
2) The coherent groups are independent of the level of detail used in modeling the generating unit.

The first assumption is based on the observation that the coherency behavior of a generator is not significantly changed as the clearing time of a specific fault is increased. Although the amount of detail of the generator model can affect the simulated swing curve, it does not radically change the basic network characteristics such as interarea modes. This forms the basis of the second assumption.

B. Slow Coherency

Slow coherency assumes that the state variables of an nth order system are divided into r slow states Y, and (n-r) fast states Z, in which the r slowest states represent r groups with the slow coherency.

Slow coherency solves the problem of identifying theoretically the weakest connection in a complex power system network. Previous work shows that groups of generators with slow coherency may be determined using Gaussian elimination on the eigensubspace matrix after selection of r slowest modes σ_a. In [2], it has been proven through linear analysis that with selection of the r slowest modes, the aggregated system will have the weakest connection between groups of generators.

The weak connection form best states the reason for islanding based on slow coherency grouping. That is, when the disturbance happens, it is required to separate in the transient time scale the fast dynamics, which could propagate the disturbance very quickly, by islanding on the weak connections. The slow dynamics will mostly remain constant or change slowly on the tie lines between the areas.

Slow coherency is actually a physical evidence of a weak connection, which is a network characteristic. In many large-scale practical systems, there always exist groups of strongly interacting units with weak connections between groups. However, even very weak connections can become strong connections with significant interactions after a short period of time. When a large disturbance happens, it is imperative to disconnect the weak connections before the slow interaction becomes significant, or before the fast dynamics propagate.

IV. Minimal cutsets based islanding

A. Motivation

Power systems are composed of buses and transmission lines connecting them. There are generator buses and load buses with various capacities. Electrical power flows among those transmission lines with certain direction. Therefore, it is very convenient to consider a power system network as a directed graph with different weights at vertices.

One of the most important requirements for islanding is to minimize the real power imbalance within the islands to benefit the restoration. After an island is formed, the imbalance between the real power supply and load demand is usually calculated by computing all the generator vertices and load vertices [12], which needs much computation. One may ask the question: What if we consider the branches connecting this island with other islands instead of browsing all vertices within this island? This intuitively makes sense, because most of the time, the number of tripping line is limited in order to form an island.

The power flows in the transmission line also contain information of the distribution of the generators throughout the system. Once the island is formed, the net flow in the tripping lines indicates exactly how different the real generation and load is within the island (we assume that the losses can be ignored).

Therefore, the problem has been converted into searching the minimal cutsets (MCs) to construct the island with the minimal net flow. We can decompose the islanding problem into two stages:

1. Find Minimal Cutsets;
2. Obtain Optimal Minimal Cutset by various criteria.

Generally, the edge searching approach may cause inefficiency in computation, because basically, there are more edges than vertices in the network. However, most of the power systems, at the transmission level, are sparse, which does not make much of a difference between vertex and edge in terms of numbers.

The advantage of this method is that we can decompose the islanding problem into two stages: In the first stage, we find the cutsets disconnecting the sets of generators; in the second stage, we check the net flow on each cutset to obtain the optimal cutset. Another advantage is that, in the second stage, we can apply any additional criteria to formulate the optimization procedure under different conditions, such as the requirements for system restoration, while the first stage remains unchanged. Furthermore, this approach is fully compatible with other techniques. This approach does not depend on slow coherency. When other grouping techniques are available, they can be adapted into this approach.

Other advantages of this method are that, besides those general criteria mentioned before, other user-specified requirements can also be included during islanding, such as,

1. Specify which line will not be disconnected. This is simply done by blocking line from the cutsets candidates.
2. Specify which area will remain untouched. This can be done by aggregating this area into one bus.

In order to demonstrate the applicability of this idea, an automatic power system islanding program has been developed to automatically determine where to create the island using minimal cutsets and breadth first searching (BFS) flag based depth first searching (DFS) technique in Graph Theory. Fig. 1 illustrates the software structure of this approach. It is composed of four main components.

1. Network reduction;
2. Generate modified BFS tree with no offspring in sink vertex;
3. With BFS flag, DFS search will be conducted to enumerate all possible MCs;
4. Islanding criteria will be applied to select the optimal MC.

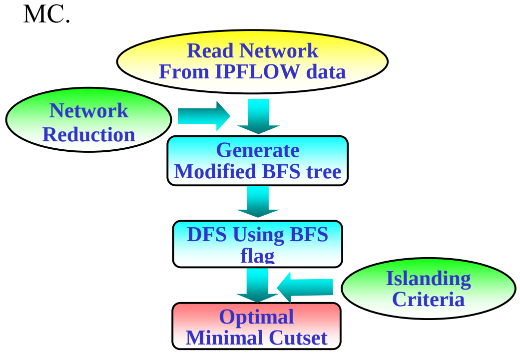

Fig. 1 Software structure

V. Two Comprehensive Approaches to System Islanding

As addressed above, by using the proposed approach a feasible solution to the islanding problem can be found. Without loss of generality, consider the islands formed in Fig. 2, H_1, H_2, and H_3 are the total inertia of the load rich islands; H_4 is the total inertia of a generation rich island.

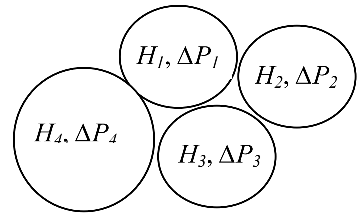

Fig. 2 Islands with feasible cutsets

From the load-generation balance point of view, the optimal solution is to minimize the net flow of each of the islands: H_1, H_2, and H_3, while maintaining $\Delta P_i/H_i$ constant among the islands H_1, H_2 and H_3, which means that the average real power imbalance per inertia should kept the same as much as possible among those load rich islands. Here reactive power requirement and other restoration criteria have not been taken into consideration.

Two applicable approaches to deal with the optimization are presented as the following:

1. Tuning Trial-Error Iterations

A tuning Index is first defined. This index indicates the degree to which each island needs to be tuned. Obviously, islands with high values of $\Delta P/H$ have a high tuning index. These values are expressed as a vector, say $[\Delta P_i/H_i]$ and denoted as the TI vector.

The algorithm will then expand the islands having the least TI among those which have intersections with the islands having largest TI. The aim is to reduce the largest TI, which increase the least TI.

An island can be expanded by including its outline. However, one should keep in mind that the expansion should exclude the generators in other islands. Minimum spanning tree (MST) techniques can be used to keep the generator buses from being included. This would also give maximal space for neighboring islands to expand.

As an example considered in Fig. 2, suppose H_1 has the largest TI, and H_2 has the least TI among those islands which intersect with H_1. H_2 will be expanded by including its outline.

In general this approach will not reach the optimal solution in a single tuning procedure. Several iterations are needed till the error computed as the following, is less than a certain tolerance.

$$\varepsilon = \sqrt{\sum_i \frac{\left(\frac{\Delta P_i}{H_i} - \frac{\overline{\Delta P}}{H}\right)^2}{n}} \tag{1}$$

where, $\frac{\overline{\Delta P}}{H} = \frac{1}{n}\sum_i \frac{\Delta P_i}{H_i}$

2. Aggregated Island Approach

An alternative to find the optimal cutset for all islands will be addressed below:

1) Based on the Tuning Indices, find the reasonable cutsets for all the generator groups.
2) Determine the load rich islands.
3) Consider all those generators in load rich islands as one group, and find out the minimal cutsets for this aggregated group with minimal net flow, which indicates the aggregated islands.
4) Assume that once the minimal cutset for the aggregated group is acquired the optimal cutset for these individual groups can always be found.
5) Calculate the load-generation imbalance within the aggregated islands. If only the load-generation imbalance is considered, $\Delta P_i/H_i$ among those individual islands should be maintained to be the same. By applying this principle, the load-generation imbalances within each individual island can be calculated.
6) Taking other criteria considering restoration into account; based on appropriate priority indices, the islanding procedure can be re-run again with the estimation of the load-generation imbalance within each island

If some load rich islands are interconnected with each other, the minimal cutsets for the aggregated island is nothing but the combination of the minimal cutsets. Here only one aggregated island is taken into consideration. For the system in which multiple aggregated islands exist, method A should be used. At first, the number of islands existing in the system should be determined. Second, by using method 1, connected islands are considered as one island, only isolated islands are taken into account. By using method 2, tune each isolated island to reach the condition where equation (1) holds. The procedure is shown in Fig. 3 as below.

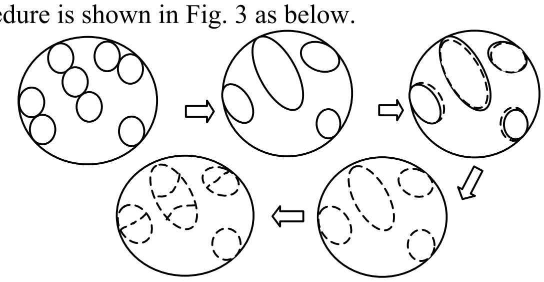

Fig. 3 Final approach to system islanding

For an aggregated island containing less than two individual islands, separation is much easier. If we want to separate individual islands in an aggregated island that has more than two islands, we need to first specify the source vertices *S* and sink vertices *T*. Usually *S* is the set of generators for one individual island, and *T* the set for another. For the case that there are more than two islands in the aggregated island, *T* includes all the generators for the rest of the area excluding *S*, as shown in step 1, Fig. 4,

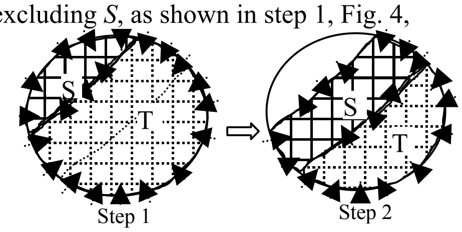

Fig. 4 Separate individual islands in one aggregated island

VI. Results From Sample System

A. Grouping Result for the Base Case

In this section we will demonstrate the efficacy of the slow coherency based grouping and the automatic islanding by using minimal cutsets on a 179-Bus, 29-Generator test system. The system has a total generation of 61410MW and 12325Mvar. It has a total load of 60785MW and 15351Mvar. The Dynamic Reduction Program (DYNRED) in the Power System Analysis Package (PSAPAC) [17] was chosen to form groups of coherent generators based on an improvement to the slow coherency method developed by GE [18] to deal with large systems and achieve more precise results. The user can specify the tolerance value, the number of slow modes, and the number of eigenvalues being calculated. Then with the help of the automatic islanding program, we determine the optimal minimal cutsets of the island taking into account the least generation load imbalance and topological requirements.

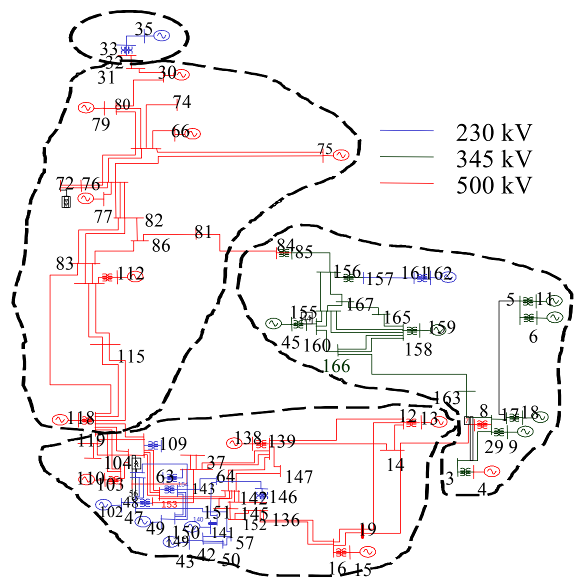

Fig. 5 Generator groups formed by slow coherency

The DYNRED program was employed to find groups of generators with slow coherency on the 179-Bus system on a base case. The 29 generators are divided into 4 groups by the slow coherency program as shown by the dotted lines in Fig. 3. Fast dynamics are propagated through the weak connections determined by the boundary between groups of generators. To develop a better understanding of the proposed approach, the minimal cutsets between the South Island and the rest of the system are first determined. Once the minimal cutset of the south island are found, we can continue to find other islands by removing the south island from the network and treating the rest of network as the whole network.

B. Graph Representation

Fig. 6 denotes the graph representation of the WECC 29-generator, 179-bus system, where buses in the biggest font designate the generator buses in the south island and buses in middle sized font indicate the generator buses in other islands.

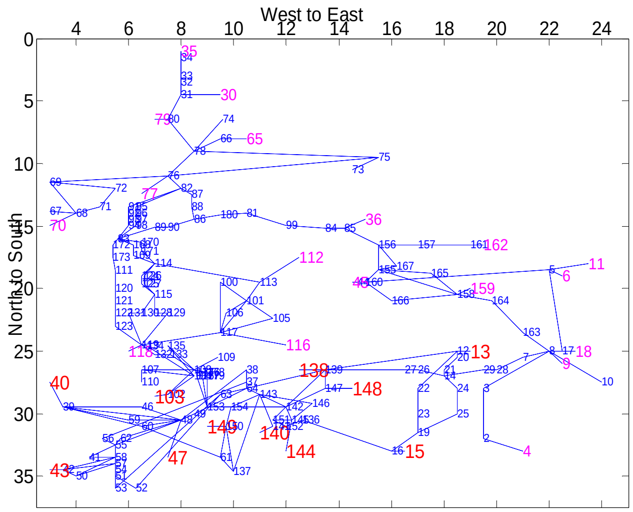

Fig. 6 Graph of WECC 29-179 System

Based on the assumption given earlier, S and T should both be connected. To achieve this, other buses are included to make the set of Gen buses in south island and the set of Gen buses in the rest of the area both connected with the minimum spanning tree technique. Then the network is reduced to a 21-vertex graph after applying vertices contraction, shown below.

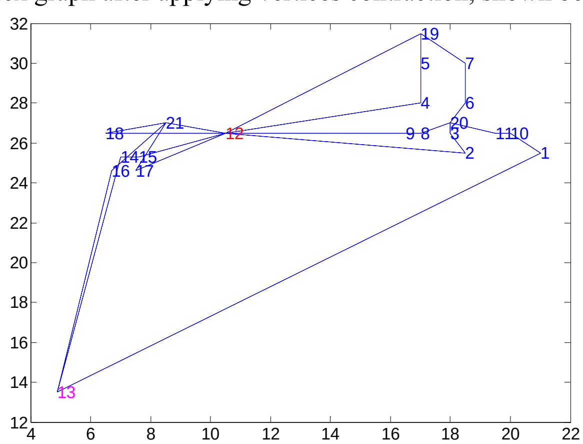

Fig. 7 network representation after vertices contraction

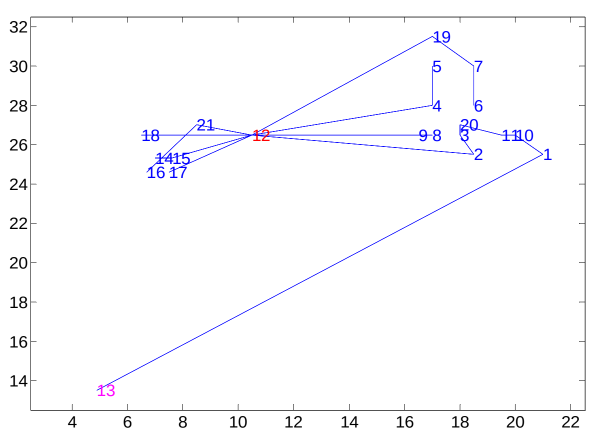

Fig. 8 modified BFS tree

In Fig. 7, vertex 12 is the source vertex, which is the aggregated vertex of the extensive Gen buses in the south island, and vertex 13 is the sink vertex, which is the aggregated vertex of the extensive Gen buses in the rest of the network. During the vertices contraction, other buses are included to make the set of Gen buses in south island and the set of Gen buses in the rest of the network both connected.

Starting with the source vertex 12, the modified BFS tree is obtained as shown in Fig. 8.

A recursive function with BFS tree flag based DFS searching technique returns the following choices of 24 minimal cutsets with 3 lines, 210 cutsets with 5 lines, 162 cutsets with 6 lines, 324 cutsets with 7 lines, and 324 cutsets with 8 lines. Table I summarizes the minimal cutsets with different number of lines and minimal load-generation imbalance.

TABLE I

MINIMAL CUSETS WITH DIFFERENT NUMBER OF LINES REMOVED

No. of lines removed	3	5	6	7	8
Cutsets number	24	210	162	324	324
Minimal Cutset with Minimal active power imbalance	14 29 104 134 108 133	102 104 14 29 108 133 108 135 108 107	16 19 12 20 12 22 104 134 139 27 108 133	102 104 19 25 12 20 139 27 108 133 108 135 108 107	16 19 102 104 12 20 12 22 139 27 108 133 108 135 108 107
Net Flow (MW)	-2076.35	-1464.98	-1434. 17	-1442. 28	-822.80

Fig. 9 shows the relationship between the number of lines removed and load generation imbalance within the island. It is very clear that there exists a trade-off: with more lines removed, there exists less imbalance.

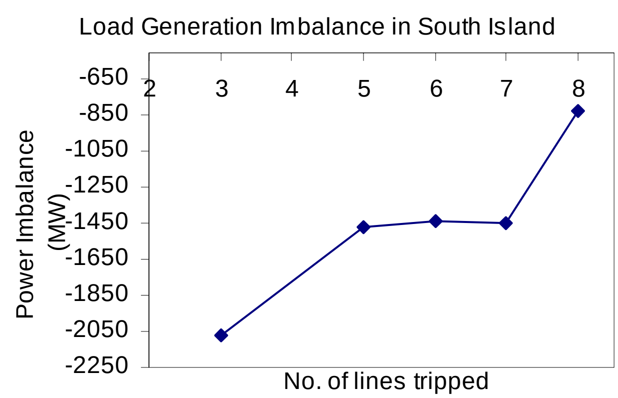

Fig. 9 Relationship number of line removed v.s. active power imbalance

It is a little bit complicated when a major contingency is being taken into account. In this approach for the reason of comparison, we have applied the same contingency as in Test Case for Set 1 Case 3 in [12], which actually cuts this WECC system in the East. According to the method mentioned in Section V, in order to handle the system with more than two islands, either Tuning Trial-Error or Aggregated Island approach may be used to form the island in a systematic manner. In this case, the Aggregated Island approach is applied to island the system into two subsystems (one load rich, another is generation rich), along with the contingency. Once this is done, the Trial-Error approach is conducted in the aggregated load rich island to form two islands out of it.

Table II denotes some information about the load rich island after the Aggregated Island approach is applied.

TABLE II
AGGREGATED LOAD RICH ISLAND

	Generator (Bus No.)	Cutset (Bus No.)	Inertia (S)	Net Flow (MW)	TI (MW/S)
Aggregated Load Rich Island	15, 103, 148, 13, 43, 144, 149,140, 40, 138, 47, 112, 116, 118	168 83 170 83 172 83 14 29	1310.05	-4106.71	-3.1348

Two islands have been created by applying the Tuning Trial-Error approach in the aggregated island. Table III illustrates the detailed information of these two islands. The last column intuitively gives the idea of how fast the rotor angle of generators on average in this island will move once the island is actually formed. It is expected that the TI values for island 1 and 2 will be the same. However, depending on the topology of this real case, these values are not the same, while they are as close as possible.

TABLE III
DETAIL INFORMATION OF TWO ISLANDS IN SOUTH

	Generator (Bus No.)	Cutset (Bus No.)	Inertia (S)	Net Flow (MW)	TI (MW/S)
Island 1	15, 103, 148, 13, 43, 144, 149,140, 40, 138, 47	**132 119** **134 119** 14 29	966.66	-2084.46	-2.1563
Island 2	112, 116, 118	168 83 170 83 172 83 **119 132** **119 134**	343.39	-2022.24	-5.8891

Fig. 10 shows the final cutsets to island the system.

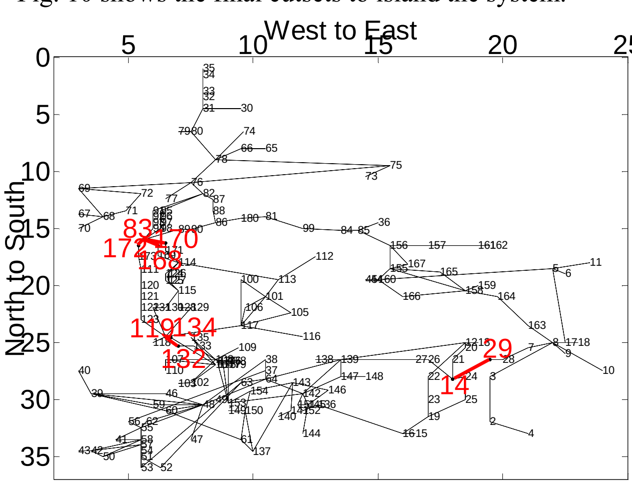

Fig. 10 Final cutsets to island the system

VII. CONCLUSIONS AND FUTURE WORK

In this paper a new approach using the minimal cutsets with minimum net flow to island the system following large disturbances has been presented.

In the future, given the minimal cutsets with different number of lines removed, dynamic simulation will be conducted to observe the influence on the system transient.

Issues regarding the restoration process will also be analyzed.

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IX. BIOGRAPHIES

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